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The Estimated Effect of Mass or Footprint Reduction in Recent Light-Duty Vehicles on U.S. Societal Fatality Risk per Vehicle Mile Traveled

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Abstract

The National Highway Traffic Safety Administration (NHTSA) recently updated its 2003 and 2010 logistic regression analyses of the effect of a reduction in light-duty vehicle mass on US societal fatality risk per vehicle mile travelled (VMT; Kahane 2012). Societal fatality risk includes the risk to both the occupants of the case vehicle as well as any crash partner or pedestrians. The current analysis is the most thorough investigation of this issue to date. This paper replicates the Kahane analysis and extends it by testing the sensitivity of his results to changes in the definition of risk, and the data and control variables used in the regression models. An assessment by Lawrence Berkeley National Laboratory (LBNL) indicates that the estimated effect of mass reduction on risk is smaller than in Kahane's previous studies, and is statistically non-significant for all but the lightest cars (Wenzel 2012a). The estimated effects of a reduction in mass or footprint (i.e. wheelbase times track width) are small relative to other vehicle, driver, and crash variables used in the regression models. The recent historical correlation between mass and footprint is not so large to prohibit including both variables in the same regression model; excluding footprint from the model, i.e. allowing footprint to decrease with mass, increases the estimated detrimental effect of mass reduction on risk in cars and crossover utility vehicles (CUVs)/minivans, but has virtually no effect on light trucks. Analysis by footprint deciles indicates that risk does not consistently increase with reduced mass for vehicles of similar footprint. Finally, the estimated effects of mass and footprint reduction are sensitive to the measure of exposure used (fatalities per induced exposure crash, rather than per VMT), as well as other changes in the data or control variables used. It appears that the safety penalty from lower mass can be mitigated with careful vehicle design, and that manufacturers can reduce mass as a strategy to increase their vehicles' fuel economy and reduce greenhouse gas emissions without necessarily compromising societal safety.

Keywords: Fatality risk, logistic regression, vehicle mass, vehicle footprint

1. Introduction

The relationship between vehicle mass and safety has been debated for many years. This debate has become more relevant with the advent of much more stringent U.S. fuel economy and greenhouse gas emission standards for new light-duty vehicles. Reducing vehicle mass is perhaps the easiest and least expensive method to improve fuel economy and reduce greenhouse gas emissions. For this reason the new U.S. standards are based on the footprint (wheelbase times track width) of each vehicle, with more stringent standards for smaller vehicles; the intent is to encourage manufacturers to make vehicles lighter to meet the standards while maintaining size, without compromising safety.

There is a widely held belief that reductions in a vehicle's mass will inherently reduce its ability to protect its occupants in a crash. One often hears that the laws of physics dictate that, all else being equal, a lighter vehicle is more risky than a heavier one. Technically this statement may be true, at least in crashes between two light-duty vehicles: as the mass differential between the two vehicles increases, the delta V (change in velocity) for the lighter vehicle, and therefore the risk to its occupants, increases relative to that of the heavier vehicle. However any reduction in risk to occupants of the heavier vehicle will be offset at least to some extent by increase in risk to occupants of the lighter vehicle. In crashes between a light-duty vehicle and a medium- or heavy-duty truck, additional mass in the light-duty vehicle would transfer more of its momentum to the truck, reducing the delta V of, and fatality risk in, the light vehicle without increasing the risk in the heavier vehicle. And additional mass may be sufficient to knock down objects such as small trees or poles, allowing the vehicle to continue moving and reducing its delta V than if it was completely stopped by the object. On the other hand, there are situations where lower mass is expected to <u>reduce</u> fatality risk: in crashes with an immovable stationary object, reducing the mass of a vehicle while maintaining its crush space and structural strength would lower the kinetic energy of the crash, reducing the amount of energy for the vehicle's structure to absorb, and likely reducing occupant fatality risk; and in rollovers, reducing mass without changing the vehicle's roof structure would reduce the force applied on the roof once a vehicle turns over.

Changing the size of a vehicle is expected to reduce risk in several ways. Increasing wheelbase or track width, or better yet frontal or side overhang, can increase crush space and reduce risk in all types of crashes. Adding to a vehicle's track width also increases a vehicle's static stability, and reduces its propensity to rollover.

Changing other vehicle dimensions also can reduce risk. Lowering bumpers or the "average height of force" in larger, heavier vehicles such as pickups and SUVs can make them more compatible with cars, and reduce risk to occupants in crash partner vehicles. Similarly, raising the door sill of a car provides more structure to engage with a bumper of a taller vehicle, such as a pickup or SUV, striking the car in the side. And lowering the center of gravity also is important in increasing stability and preventing rollovers. Finally, strengthening a vehicle's frontal or side structure can increase the amount of energy it can absorb in all types of crashes; however, increasing frontal stiffness will likely have negative impacts on the occupants of a crash partner in a frontal collision.

All of these hypothetical effects of the changes in vehicle mass, footprint, or other dimensions assume no other changes to the vehicle. However, this is rarely the case, as often the source of the additional mass is the installation of a particular safety feature (such as 4-wheel drive or ESC), and manufacturers often make other changes to a vehicle design at the same time they change its mass or footprint. In short, it is possible that other changes in vehicle design, as well as introduction of safety technologies, can mitigate any increase in risk from reducing vehicle mass or footprint.

A complication of course is that, in the real world, all else is never equal: the behavior of drivers and fragility of occupants; the time, location, weather, and circumstances of the event; and design details of the vehicles involved, including specific safety features installed and other more general aspects of vehicle design, all contribute to the outcome of any particular crash. And the effect of additional vehicle mass on occupant, and crash partner, risk depends on where and how it is added to a vehicle. In summary, the complexity of the factors in vehicle design and operation makes it extremely difficult to isolate their effect on occupant and societal risk.

Over two decades the National Highway Traffic Safety Administration (NHTSA) has conducted three thorough analyses estimating the effect of mass reduction on U.S. fatality risk (Kahane 1997, 2003, 2010). These studies have used logistic regression analysis to examine the societal risk of fatality per vehicle mile traveled (VMT), in different vehicle types and in different types of crashes, including variables to control for several other factors thought to influence fatality risk, such as driver age and gender, crash time and location, and other vehicle attributes. Societal risk includes fatalities in the case vehicle as well as any crash partners; using VMT as the measure of exposure accounts for a vehicle's ability to protect its occupants and others once a crash has occurred (crashworthiness/crash compatibility), as well as the capability of the vehicle to avoid a serious crash altogether (crash avoidance). The most recent of these studies, in 2003, have found that, after accounting for all the other factors that influence fatality risk, a 45-kg reduction in vehicle mass is associated with an increase in fatality risk per VMT, from a 0.5% increase (or 71 additional deaths per year) for heavier-than-average light trucks to a 4.4% increase (or 597 additional deaths per year) for lighter-than-average cars, depending on the type of vehicle (Kahane 2003; Wenzel and Ross 2006).

Using a method similar to NHTSA, Dynamic Research, Inc. (DRI) showed that regression analyses that included both mass and size (i.e. wheelbase and track width) in the same regression model (i.e. that estimated the effect of mass while holding size constant, and vice versa) estimated smaller effects for changes in mass or size on US fatality risk per VMT (Van Auken and Zellner, 2002, 2003, 2004, 2005a, 2005b, 2012a, 2012b). In his 2010 update of the 2003 analysis, Kahane included both mass and size (i.e. footprint, or wheelbase times track width) in the same regression model, in part because the model year 2012 to 2016 light truck standards adopted in 2010, and the proposed 2017 to 2025 standards for all light-duty vehicles, assign a target fuel economy/greenhouse gas emission level based on a vehicle's footprint (Kahane 2010). The 2010 update estimated that fatality risk in heavier-than-average light trucks would be reduced by 1.9%, and fatality risk in lighter-than-average cars increased by only 2.2%, if mass was reduced while holding footprint constant.

NHTSA recently completed an update of its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per vehicle mile traveled, in support of the upcoming joint rulemaking on new fuel economy and greenhouse gas emission standards for new vehicles sold in 2017 to 2025 (Kahane 2012). Lawrence Berkeley National Laboratory (LBNL) used the same data and methods to replicate NHTSA's analysis, examined the effect of changing the data and control variables used in their regression models, and analyzed the relationship between mass reduction and risk by vehicle model. This paper summarizes our analysis of the sensitivity of

Kahane's results to changes in the data and control variables used in its regression analyses (Wenzel 2012a).

There are several aspects of the LBNL, NHTSA, and DRI analyses that distinguish them from other efforts. First, they measure societal risk: all fatalities, including passengers, in all types of crashes, including those in the crash partner in two-vehicle crashes and pedestrians and cyclists, are included. Second, societal risk is estimated per vehicle mile travelled, which accounts for both a vehicle's crashworthiness/compatibility and its ability to avoid a serious crash. And third, vehicle mass and footprint, as well as installed safety features, driver age and gender, and crash circumstances, are controlled for.

Several studies have estimated the relationship between mass, or mass ratio, and risk. Analysis of crashes between two cars found that ratio of fatalities to the two drivers increases in the lighter car as the ratio of masses between the two cars increases (Evans 2004a and 2004b). Broughton (1996a, 1996b, 1996c) updated the Evans analyses for the U.K. and extended it to casualties (fatalities and serious injuries requiring hospitalization), while controlling for roadway speed limit (an indicator of the relative crash severity), driver gender and age, and point of initial impact. Several have conducted regression analyses to estimate the effect of vehicle mass, or mass ratio, on driver fatality or casualty risk per crash, usually in two-vehicle crashes (Toy and Hammitt 2003; Fredette et al. 2008; Martin and Lenguerrand 2008; Tolouei and Titheridge 2009; Eyges and Padmanaban 2009). By using crashes as the measure of exposure, these studies examined the relationship of mass on vehicle crashworthiness/compatibility only. LBNL recently examined the relationship between vehicle mass and crashworthiness/compatibility elsewhere (Wenzel 2012b).

Broughton (2008, 2012) used logistic regression to estimate the effect of mass on fatality and casualty risk per vehicle registration-year; however, he did not include all types of crashes, account for vehicle size (other than six size classes of vehicles), or analyze risk per vehicle mile traveled. The one study that has explicitly estimated the effect of mass reduction on all fatalities in all vehicles, per vehicle mile traveled, did not include crashes involving pedestrians and cyclists, and did not account for vehicle size (Kim et al. 2006).

2. Data and methods

Information on all U.S. traffic fatalities in crashes involving model year 2000 to 2007 light-duty vehicles that occurred between 2002 and 2008, from the Fatality Analysis Reporting System (FARS) were used in the regression analyses. Fatalities include those in both the case vehicles and any of their crash partners, such as medium- and heavy-duty vehicles, motorcycles, bicyclists, and pedestrians. Separate regression models were run for each of three types of vehicles (passenger cars, light-duty trucks, and car-based crossover utility vehicles, or CUVs, and minivans), and for each of nine types of crashes (first-event rollovers; crashes with stationary objects, motorcycles/bicycles/pedestrians, heavy-duty vehicles, and four categories of other light-duty vehicles; and all other crashes, most involving three or more vehicles) for a total of 27 regression models. Crashes with another light-duty vehicle were categorized into four types based on the type and weight of the crash partner: a car, CUV or minivan lighter or heavier than average (1,398 kg), and a pickup or truck-based SUV lighter or heavier than average (1,882 kg). Kahane excluded case vehicles that were considered “sporty” cars, cars used primarily for police use, cars with all-wheel drive, and fullsize vans from its initial analysis.

Kahane created an “induced exposure file”, using a subset of non-culpable vehicles involved in two-vehicle crashes from police-reported crash data from thirteen states, to represent crashes that did not lead to a fatality. These thirteen states (AL, FL, KS, KY, MD, MI, MO, NE, NJ, PA, WA, WI and WY) were selected because they provide the first 12 digits of the 17-digit vehicle identification number (VIN) that can be decoded to determine the model year and model of each vehicle. These records provide distributions of a random sample of on-road vehicles by vehicle year, make, and model; driver age and gender; and crash time and location (day vs. night, rural vs. urban counties, and high-speed roads). Kahane then gave each induced exposure record a weighting factor, so that each represents a number of national vehicle registrations of a particular model year, make and model; the sum of the weighting factors equals the number of vehicles registered in the country. Each record was also given an annual vehicle miles traveled (VMT) weighting factor, based on vehicle year, make/model, and age, using odometer data provided by R.L. Polk and Co. NHTSA’s databases of fatal crashes, and of induced-exposure crashes used to develop national vehicle registration and annual miles traveled weights, are available for download at: ftp://ftp.nhtsa.dot.gov/CAFE/; for more details on NHTSA’s data and methodology, refer to Kahane 2012.

The databases of fatal crashes and induced exposure cases were combined, in order to estimate the likelihood that a given vehicle/driver combination driven over a certain number of miles results in a crash fatality. The analysis involved running a logistic regression model with total crash fatalities as the dependent variable for each of the nine crash types and the three vehicle types, for a total of 27 regressions. Because all fatalities in the crash were used, the risks reflect societal risk, rather than just the risk to the occupants of the case vehicle. The induced exposure cases were weighted by the number of vehicle registrations and the annual mileage, so that the models are estimating the effect of changes in the control variables on US societal fatalities per vehicle mile traveled (VMT).

NHTSA compiled a database of curb weight and footprint, as well as other vehicle attributes, by model year, make and model. For cars and trucks, one of two weight variables was used, depending on the weight of the vehicle: for relatively light vehicles UNDRWT00, the number of kg less than the average vehicle weight, was used, while OVERWT00, the number of kg greater than the average vehicles, was used for heavier vehicles. This two-piece variable for weight allows the effect of weight on risk to vary for lighter- and heavier-than-average vehicles. The determination of the two weight classes is based on the average weight for model year 2000 to 2007 versions of each vehicle type: 1,433 kg for cars and 2,247 kg for light-duty trucks. Because there are fewer CUVs and minivans in the database, a single variable, LBS100, was used for CUV/minivan weight. A variable for the vehicle footprint, which is its wheelbase times its track width, is included in the models (FOOTPRNT), as the U.S. fuel economy and emission standards vary based on an individual vehicle’s footprint (with vehicles having a larger footprint having a less-stringent standard). The footprint-based standards were introduced in the U.S. to encourage manufacturers to make vehicles lighter without necessarily making them smaller, in an effort to maintain occupant safety.

Control variables were used for two door cars, truck-based SUVs, heavy-duty (i.e. 3/4- and 1-ton rated) pickups, and minivans. Several new variables were added for new safety technologies and designs that were not included in the previous studies: electronic stability controls (ESC), four types of side airbags (ROLLCURT, CURTAIN, COMBO, TORSO),[1] and two methods to comply with the voluntary manufacturer agreement to better align light truck bumpers to make them more compatible with other types of vehicles (BLOCKER1, BLOCKER2). Vehicles with automated braking systems (ABS) and all-wheel drive (AWD) were identified, as was the vehicle age and whether the vehicle was brand new (i.e. vehicle age of zero). Eight variables for driver age and gender were used, in addition to whether the driver was male. To account for crash conditions, control variables for whether the crash occurred at night-time, in a rural county, on a roadway with a speed limit of 55 miles per hour or greater, or in a state that has a relatively high fatality rate per VMT, as well as the calendar year in which the crash occurs, were included. As noted in Table 1, not all control variables were used in the regression models for each type of vehicle or crash.

Rather than reporting coefficients for the variables of interest (curb weight and footprint) from a single regression model across all crash types, Kahane reported a weighted average of the coefficients from the nine regression models run for each of the nine crash types. Kahane used a "baseline" distribution of fatalities across the crash types, to represent the expected distribution of fatalities in the 2017 to 2025 timeframe of the new CAFE and GHG emission standards. Similar to the 2003 study, Kahane derived the baseline fatalities from MY04-09 vehicles in crashes between 2004 and 2008. Kahane then adjusted this baseline distribution of fatalities downward to account for the assumption that all vehicles in the 2017-2025 timeframe will have ESC installed. The assumptions used for this adjustment are taken from a NHTSA analysis that found that ESC reduces fatal rollovers by 56% in cars and 74% in light trucks; fixed-object impacts by 47% in cars and 45% in light trucks; and other non-pedestrian crashes by 8% in both cars and light trucks (Sivinski 2011). These assumptions treated CUVs and minivans as light trucks rather than cars. This "post-ESC" distribution of fatalities by crash type was then multiplied by the regression coefficients for each crash type to create the weighted average effect of each control variable on risk.

All of the regression coefficients presented in the NHTSA 2012 report are the direct output from the SAS LOGIST procedure (with the exception of those for the mass and footprint variables UNDRWT00, OVERWT00, LBS100, and FOOTPRNT, which Kahane multiplies by -1 so that they reflect the effect of a decrease in vehicle mass or footprint; the same convention is used throughout this report). The output from the SAS LOGIST procedure reflects the percent change in the log-odds of fatality per billion VMT for a one-unit increase in the explanatory variable. In order to obtain the percent change in the probability of fatality, the SAS outputs need to be converted from log-space to linear space, and from odds to probabilities. The equation $e^x - 1$, where x is the logistic regression coefficient from the SAS output, is used to make this conversion. This conversion has no effect on the output regression coefficients when the change

[1] The control variable ROLLCURT airbags was included only in the regression models for rollover crashes involving cars or CUVs/minivans; regression models of pedestrian crashes did not include any control variables for airbags; and the control variables for CURTAIN, COMBO, and TORSO airbags were included in regression models for all other crashes involving cars or CUVs/minivans. No airbag variables were included in the regression models for light trucks.

in the log-odds of fatality is small; however it substantially increases the percent change for explanatory variables that have a large effect on the log-odds of fatality (such as the crash location variables). For example, the fatality risk from a rollover crash involving a car has a 2.20 times higher log-odds of fatality if it occurs in a rural county; after conversion, this crash has a 802 percent higher probability of fatality if it occurs in a rural county (EXP(2.20) - 1 = 8.02). The 95% confidence intervals reported here are calculated the same way, using the standard error of the log-odds output by the SAS LOGIST procedure.

Although the purpose of these analyses is to estimate the effect of vehicle mass reduction on societal risk, this is not exactly what the regression models are estimating. Rather, they are estimating the recent historical relationship between mass and risk, after accounting for most measurable differences between vehicles, drivers, and crash times and locations. In essence, the regression models are comparing the risk of a 1180-kg Dodge Neon with that of a 1134-kg Honda Civic, after attempting to account for all other differences between the two vehicles. The models are <u>not</u> estimating the effect of literally removing 45 kg from the Neon, leaving everything else unchanged.

In addition, the analyses are based on the relationship of vehicle mass and footprint on risk for recent vehicle designs (model year 2000 to 2007). These relationships may or may not continue into the future as manufacturers utilize new vehicle designs and incorporate new technologies, such as more extensive use of strong lightweight materials and specific safety technologies. Therefore, throughout this paper the phrase "the estimated effect of mass (or footprint) reduction on risk" is used as shorthand for "the estimated change in risk as a function of its relationship to mass (or footprint) for vehicle models of recent design."

3. Results

Table 1 presents the estimated coefficients for all of the variables included in the regression models; the coefficients for each of the 9 crash types are weighted by the distribution of 2016 baseline fatal crash involvements, after adjustment for full ESC penetration, as described above. (The coefficients for the variables of interest, UNDRWT00, OVERWT00, LBS100, and FOOTPRNT, are slightly different from those provided in the 2012 NHTSA report, perhaps because of rounding errors and our reporting of percent changes in risk as probabilities rather than as log-odds.) The table indicates that a 45-kg reduction in vehicle mass is associated with a roughly one percent increase in societal fatality risk for cars and lighter-than-average light trucks, while mass reduction is associated with a slight reduction in fatality risk for the heavier light trucks and CUV/minivans. The estimated changes in risk for lighter cars, and both categories of light-duty trucks, are statistically significant. Statistical significance is estimated based on the 95% confidence intervals: the weighted average standard error from the SAS output times 1.96. Kahane does not report these confidence intervals in his 2012 report; rather he uses a jack-knife technique to estimate the range in uncertainty around the point estimates. The technique involves running multiple regression models on 10 random subsamples of the fatality data, and 11 random subsamples of the state induced exposure data; the confidence intervals are constructed from the standard errors of these subsamples (Kahane 2012, pp. 63-66). The resulting confidence intervals are slightly larger than those shown here. As a result, NHTSA's 2012 report indicates that only the estimated 1.55% increase in risk from mass reduction for the lighter cars is statistically significant. Table 1 also indicates that a 0.09 square meter reduction in footprint increases fatality risk in cars and CUVs/minivans by close to 2 percent, but has no effect on risk in light trucks. Based in part on these estimates, the fuel economy and greenhouse gas emission standard levels adopted in 2012 assume that it is cost effective for manufacturers to reduce the mass of light trucks by up to 20% without increasing societal risk; the standard levels allow for a reduction in mass of up to 10% for large cars, and up to 3.5% for midsize cars (U.S. EPA and NHTSA 2012).

Table 1 also compares the estimated effect of mass or footprint reduction on risk with that of the other control variables, by vehicle type. The table indicates that two-door cars and truck-based SUVs are associated with an 8% increase in US fatality risk per VMT compared to four-door cars and pickup trucks, respectively. Heavy-duty (200 or 300 series, rated ¾-ton or 1-ton) pickups are estimated to have slightly higher risk than smaller pickups, while minivans slightly lower risk than CUVs. TORSO side airbags in cars are associated with a 9% reduction in risk, while COMBO side airbags are estimated to reduce risk in CUVs/minivans by 6%. Automated braking systems (ABS) are estimated to reduce risk in cars (8%) and CUVs/minivans (17%); electronic stability control (ESC) is estimated to risk in cars (12%) and light trucks (19%), but only by 4% in CUVs/minivans; and all-wheel drive (AWD) is estimated to reduce risk in both light trucks and CUVs/minivans by about 14%. Two variables are included to identify approaches to comply with voluntary measures to reduce light truck aggressivity towards cars: BLOCKER1, vertical alignment of bumpers, and BLOCKER2, employment of an additional blocker beam below the primary bumper. Each of these two approaches is associated with small, not statistically-significant, reductions in risk.

Male drivers are associated with a greater than 35% increase in risk in cars and CUVs/minivans, and with a 19% increase in light trucks. The driver age variables tend to increase risk, with young male and elderly drivers (male and female) associated with increases in risk of between 4% and 8%. Vehicle age is associated with an estimated 3% to 6% increase in risk per year of age, while a brand new car or CUV/minivan is associated with a nearly 10% increase in risk, presumably because the driver is unfamiliar with a new car's controls, handling, and/or braking capabilities. Brand new light trucks are estimated to increase risk by only 4%, which is surprising as one would think driver unfamiliarity with the handling of a light truck would increase their chance of rolling it over.

Crashes that occur at night are estimated to nearly double fatality risk per VMT, while crashes in rural areas or on high-speed roads are estimated to have an even higher effect on risk, for all three vehicle types. A crash occurring in a high-fatality state is associated with a 25% to 34% higher fatality risk than a crash in other states. In general the calendar year variables have a decreasing effect on risk over time, declining from between an estimated 6% and 22% increase in risk in 2002, depending on vehicle type, to between an estimated 15% and 20% reduction in risk in 2008.

Note that the vehicle weight (UNDRWT, OVERWT, and LBS100) and footprint variables all have a much lower estimated effect on risk than almost all of the control variables in Table 1. For instance, a 45-kg reduction in curb weight for a lighter-than-average car is estimated to increase risk by 1.55%, while installing ESC is estimated to reduce risk by 11.9%. The models

Table 1. Estimated effect of variables on U.S. societal fatality risk per VMT, weighted by the distribution of fatalities after full adoption of ESC by 2017, by case vehicle type

Type	Control variable	Description	Cars	Light trucks	CUVs/ minivans.
Vehicle variables	UNDRWT00	Lbs (in hundreds) less than average curb weight (all negative values)	1.55%*	0.52%*	—
	OVERWT00	Lbs (in hundreds) more than average curb weight (all positive values)	0.51%	-0.34%*	—
	LBS100	Lbs curb weight (in hundreds)	—	—	-0.38%
	FOOTPRINT	Wheelbase times track width, in sq feet	1.87%*	-0.07%	1.72%*
	TWODOOR	Two-door car	8.45%*		—
	SUV	Truck-based SUV	—	8.94%*	—
	HD_PKP	Heavy-duty pickup (200/300 series)	—	1.73%	—
	BLOCKER1	Option 1 compatibility (bumper overlap)	—	-1.41%	—
	BLOCKER2	Option 2 compatibility (“blocker beam”)	—	-2.32%	—
	MINIVAN	Minivan	—	—	-0.94%
	ROLLCURT#	Curtain airbag that deploys in rollovers	-0.73%	—	-1.67%*
	CURTAIN #	Curtain side airbag	1.00%	—	-2.85%
	COMBO #	Combo curtain/torso side airbag	-1.10%	—	-6.43%*
	TORSO #	Torso side airbag	-8.76%*	—	0.86%
	ABS	Automated braking system	-7.87%*	—	-16.5%*
	ESC	Electronic stability control	-11.9%*	-18.8%*	-3.89%
	AWD	All-wheel drive	—	-14.5%*	-14.0%*
	VEHAGE	Vehicle age	2.54%*	3.57%*	5.50%*
	BRANDNEW	Vehicle age = 0	10.2%*	3.62%*	8.76%*
Driver variables	DRVMALE	Driver is male	39.2%*	19.3%*	37.1%*
	M14_30	Number of years male driver is	4.63%*	3.54%*	3.92%*
	M30_50	younger than 50 years old	1.40%*	1.25%*	0.84%*
	M50_70	Number of years male driver is	2.20%*	1.24%*	1.82%*
	M70_96	older than 50 years old	8.08%*	7.65%*	7.10%*
	F14_30	Number of years female driver is	2.81%*	3.64%*	4.77%*
	F30_50	younger than 50 years old	0.09%	0.22%	-0.47%
	F50_70	Number of years female driver is	3.21%*	3.10%*	3.22%*
	F70_96	older than 50 years old	8.00%*	6.36%*	7.69%*
Crash variables	NITE	Crash occurred at night	194%*	192%*	160%*
	RURAL	Crash occurred in rural county (<250 population / square mile)	223%*	207%*	215%*
	SPDLIM55	Crash occurred on a roadway with speed limit of 55 mph or higher	414%*	409%*	405%*
	HIFAT_ST	Crash occurred in a high fatality risk state (25 Southern and Mountain states, plus KS and MO)	29.5%*	24.6%*	33.8%*
	CY2002	Crash occurred in 2002	5.56%*	22.4%*	7.59%
	CY2003	Crash occurred in 2003	3.60%*	18.2%*	4.97%
	CY2004	Crash occurred in 2004	1.69%	14.1%*	-3.28%
	CY2005	Crash occurred in 2005	-0.60%	7.86%*	0.02%
	CY2007	Crash occurred in 2007	-1.42%	-1.19%	-4.99%
	CY2008	Crash occurred in 2008	-13.3%*	-15.0%*	-19.7%*

CURTAIN, COMBO, and TORSO airbags are included in regression models for all non-rollover crashes involving cars or CUVs/minivans, except motorcycle/bicycle/pedestrian crashes. A single variable for ROLLCURT airbags replaces the CURTAIN, COMBO, and TORSO variables in the regression for rollovers.

* statistically significant at the 95% level.

estimate that the beneficial effect of adding ESC, ABS, or all-wheel drive is nearly ten times that of reducing mass by 45 kg. And male drivers, or crashes in a high fatality state, has over a 20 times larger estimated effect on societal fatality risk than a 45-kg reduction in mass, while driving at night, or on a rural or high speed road, has over a 200 times larger estimated effect on fatality risk than a 45-kg reduction in mass.

NHTSA and LBNL conducted nineteen additional regression models, to test the sensitivity of the results shown in Table 1 to different measures of risk, and different data and control variables used. Table 2 compares the estimates for the weight and footprint variables from NHTSA's "preferred" model in Table 1 with six of these alternative models. As described above, the NHTSA preferred model estimates the effect of full ESC adoption by 2017 by weighting the estimates from the regression model for each of the nine types of crashes by the expected number of fatalities after full adoption of ESC. Model 1 in Table 2 weights the estimates from the regression for each crash type by the current distribution of fatalities. Full penetration of ESC in the on-road fleet is estimated to slightly increase the safety penalty from mass reduction, as the weighted values in the NHTSA preferred model are all higher than the unweighted values (Model 1). For example, mass reduction is associated with a 1.27% increase in risk for lighter-than-average cars based on the current distribution of fatalities (Model 1), but a 1.55% increase assuming full penetration of ESC (NHTSA preferred model). On the other hand, full ESC penetration is expected to reduce the estimated safety penalty from a reduction in footprint, for all vehicle types (for example, from a 2.16% increase to a 1.87% increase for cars). All of the alternative regression models in Table 2, except Model 1, reweight the regression estimates for each type of crash by the expected number of fatalities after full adoption of ESC, according to NHTSA's method in its preferred model.

Table 2. Estimated effect of a 45-kg reduction in mass or a 0.09-m^2 reduction in footprint on U.S. societal fatality risk, under six alternative regression model specifications

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	1. Weighted by current distribution of fatalities	3. Excluding footprint or weight	8. Accounting for 19 vehicle brands	9. Accounting for initial vehicle purchase price	12 Excluding crashes involving alcohol/drugs and bad drivers	13. Accounting for median household income
Mass reduction	Cars < 1433 kg	1.55%*	1.27%*	2.74%*	2.04%*	1.42%*	2.32%*	1.20%*
	Cars > 1433 kg	0.51%	0.37%	1.95%*	1.80%*	0.84%	1.19%*	0.16%
	LTs < 2247 kg	0.52%*	0.42%*	0.47%*	0.57%*	0.45%*	1.01%*	0.68%*
	LTs > 2247 kg	-0.34%*	-0.36%*	-0.39%*	-0.11%	-0.52%*	-0.11%	-0.30%
	CUV/minivan	-0.38%	-0.70%	0.60%*	1.28%*	-0.92%	-0.01%	-0.44%
Footprint reduction	Cars	1.87%*	2.16%*	2.98%*	1.20%*	1.99%*	1.32%*	2.30%*
	LTs	-0.07%	0.14%	0.07%	-0.28%	-0.36%*	-0.39%*	-0.19%
	CUV/minivan	1.72%*	2.25%*	1.33%*	-0.28%	1.57%*	1.12%	1.82%*

* statistically significant at the 95% level.

Table 3 shows the estimated effect of changes in mass or footprint on risk, by vehicle and crash type. For cars, mass reduction is associated with an increase in risk in all crash types except rollovers and crashes with stationary objects (a 1.85% and 2.93% reduction in risk, respectively). A possible explanation for why mass reduction is estimated to reduce risk in rollovers is that once a vehicle rolls over, a lighter vehicle applies less force on its roof than a heavier vehicle. And as mentioned above, if additional mass is sufficient to knock down a stationary object such as a tree or pole, it can protect occupants; however, additional mass will increase the kinetic crash energy, and likely increase occupant risk when the object is immovable. Because Kahane assumes that by 2017 ESC will have eliminated many of the fatalities in rollovers and crashes with stationary objects, and these are the only types of crashes in which mass reduction reduces risk, NHTSA's weighted regression estimates for 2017-2025 show a larger increase in overall risk for cars (a 1.55% and 0.51% increase for lighter- and heavier-than-average cars, respectively; preferred NHTSA model in Table 2) than the estimates based on the current distribution of fatalities (a 1.27% and 0.37% increase for lighter- and heavier-than-average cars, respectively; alternate Model 1 in Table 2). For CUVs and minivans, full adoption of ESC is estimated to reduce the small overall benefit in fatality risk from mass reduction (from a 0.70% reduction to a 0.38% reduction in risk). On the other hand, footprint reduction is associated with the largest risk <u>increases</u> in rollovers and crashes with stationary objects, so removing fatalities in these types of crashes is expected to reduce the estimated detrimental effects of footprint reduction. For example, footprint reduction in cars increases risk by 7.76% in rollovers and 3.93% in crashes with a stationary object (Table 3); full adoption of ESC is expected to reduce the detrimental effect of footprint reduction in cars from a 2.16% overall increase in risk (alternate Model 1 in Table 2) to a 1.87% overall increase in risk (NHTSA preferred model in Table 2).

Table 3. Estimated effect of a 45-kg reduction in mass or a 0.09-m^2 reduction in footprint on U.S. societal fatality risk, by vehicle and crash type

	Effect of 45-kg reduction in mass					Effect of a 0.09-m^2 reduction in footprint		
Crash type	Cars < 1433 kg	Cars > 1433 kg	LTs < 2247 kg	LTs > 2247 kg	CUV/ minivan	Cars	LTs	CUV/ minivan
Rollover	-1.85%	-2.93%	0.65%	-1.29%*	-7.27%*	7.76%*	1.18%*	10.94%*
w/stationary object	-0.46%	-1.30%	-1.40%*	0.76%	-3.68%*	3.93%*	1.97%*	7.39%*
w/cycles, pedestrians	2.01%*	-0.14%	1.06%	-0.05%	-1.58%	0.91%	-1.25%*	0.37%
w/heavy-duty truck	2.24%	0.39%	1.61%	0.32%	1.92%	2.92%*	0.75%	4.56%
w/light car	0.75%	0.26%	-0.09%	-0.92%*	-0.09%	0.23%	-0.21%	-0.79%
w/heavy car	0.48%	1.61%	-0.71%	-1.38%*	1.67%	0.49%	0.31%	-2.21%
w/light light truck	1.17%	0.53%	-0.63%	-0.97%	3.75%	3.88%*	1.00%	-4.13%
w/heavy light truck	5.88%*	2.32%	4.36%*	0.53%	-0.93%	1.75%	-1.70%*	3.73%
Others	1.93%*	1.16%	0.73%	-0.11%	-0.40%	1.13%	-0.44%	2.68%*
All	1.55%*	0.51%	0.52%*	-0.34%*	-0.38%	1.87%*	-0.07%	1.72%*

* statistically significant at the 95% level.

Mass reduction in the lighter cars is associated with the biggest increase in risk (5.9%) in crashes with a heavy light truck. For heavier cars, mass reduction is associated with generally smaller increases in risk for most types of crashes. A reduction in car footprint is associated with increases risk in all types of crashes, including rollovers and crashes with stationary objects. In fact, footprint reduction is associated with the largest increases in risk in these two crash types (7.7% and 3.9%), followed by crashes with a lighter light-duty truck (3.9%) and with a heavy-duty truck (2.9%).

Table 3 suggests that, in general, the estimated effects on risk are smaller for light trucks than for cars, and there are more cases in which mass reduction is estimated to reduce risk, although the estimates are often small and not statistically-significant. Mass reduction is associated with a statistically-significant reduction in risk in lighter truck crashes with objects, and heavier truck rollovers; but (statistically-insignificant) increases in risk in lighter truck rollovers and heaver truck crashes with objects. As with light cars, the biggest estimate of mass reduction in lighter trucks is in crashes with a heavier light truck, with a 4.4% increase in risk. A reduction in light truck footprint tends to correlate with an increase in risk, although the estimated increases are small and often not statistically-significant. However, contrary to cars, footprint reduction in light trucks significantly reduces fatality risk in crashes with pedestrians and cyclists, and with heavier light trucks.

The estimated effects from mass reduction tend to be larger in CUVs and minivans than in cars or light trucks, with a greater than 7% estimated reduction in risk in rollovers and an estimated 3.7% reduction in risk in crashes with objects. Mass reduction in CUVs/minivans is associated with the most detrimental effect on risk in crashes with a light light-duty truck, a (statistically-insignificant) 3.8% increase. The estimated effect of reductions in footprint in CUVs and minivans is similar to that for cars, with a larger, statistically-significant increase in risk in rollovers (10.9%) and crashes with objects (7.4%). As with cars, Kahane's assumption of fewer fatalities in rollovers and crashes with stationary objects due to full adoption of ESC by 2017 is expected to result in an increase in the estimated effect of mass reduction (from a 0.70% decrease to a 0.38% decrease), but a decrease in the estimated effect of footprint reduction (from a 2.25% increase to a 1.72% increase), on risk in CUVs and minivans (Table 2).

3.1. Multi-collinearity between vehicle mass and footprint

In his 2003 analysis Kahane did not include vehicle mass and size in the same regression model, because the two variables were strongly correlated with each other. Using two or more variables that are strongly correlated in the same regression model (referred to as multi-collinearity) can lead to spurious results. The variance inflation factor, or VIF, is a measure of the degree of multi-collinearity in a regression model. Allison "begins to get concerned" with VIF values greater than 2.5 (Allison 1999), while Menard suggests that a VIF greater than 5 is a "cause for concern", and a VIF greater than 10 "almost certainly indicates a serious collinearity problem" (Menard 2002); however, O'Brien suggests that "values of VIF of 10, 20, 40 or even higher do not, by themselves, discount the results of regression analyses" (O'Brien 2007).

The correlation between vehicle mass and footprint may not be strong enough to cause serious concern; it ranges from a Pearson correlation coefficient r of over 0.90 for four-door sedans and SUVs, followed by small pickups and CUVs (r of 0.80) and 2-door cars (0.76). The correlation between weight and footprint is lowest for large pickups (0.67) and minivans (0.49)[2]. Six of the seven vehicle types (all except minivans) have a VIF associated with curb weight greater than 2.5, the point at which multi-collinearity becomes a concern. The 2012 NHTSA report correctly

[2] The low correlation between weight and footprint for minivans is strongly influenced by one model, the Kia Sedona, which is unusually heavy for its size; removing this model from the analysis increases the correlation of minivans to 0.63

recognizes that the "near" multicollinearity between mass and footprint may not be strong enough to invalidate the results from a regression model that includes both variables; even so, Kahane made several attempts to account for the near-multicollinearity between mass and footprint.

First, Kahane tested the effect of replacing mass or footprint with a single variable indexing mass to footprint. He estimated the expected curb weight for a particular type of vehicle and footprint, and calculated excess weight for each vehicle by subtracting the expected weight from the actual weight. The correlation between excess weight and footprint is zero. Replacing mass with the excess weight variable (or replacing footprint with an excess footprint variable) did lower VIF, but did not change the regression estimates on the control variables.

Second, Kahane ran a sensitivity model specification, where footprint is not held constant, but rather allowed to vary as mass varies (i.e. he ran a regression model which includes mass but not footprint). If the multicollinearity was so great that including both variables in the same model gave misleading results, removing footprint from the model would give much different results than keeping it in the model. As shown in Table 2, the sensitivity indicates that when footprint is allowed to vary with mass (top panel of Model 3), the estimated effect of mass reduction on risk increases to 2.74% for lighter cars, and to a statistically-significant 1.95% for heaver cars and 0.60% for CUVs/minivans; however, the estimated effect of mass reduction on light trucks is unchanged. We ran a second sensitivity which keeps footprint in the regression model, but removes mass (bottom panel of Model 3 in Table 2). Allowing vehicle mass to be reduced with footprint increases the estimated effect of a reduction in footprint on car risk, decreases the estimate of footprint reduction on CUV/minivan risk, and has essentially no effect on the estimate of a reduction in footprint on risk in light trucks.

Third, Kahane conducted a stratification analysis of the effect of mass reduction on risk by dividing vehicles into deciles based on their footprint, and running a separate regression model for each vehicle and crash type, for each footprint decile (3 vehicle types times 9 crash types times 10 deciles equals 270 regressions). This analysis estimates the effect of mass reduction on risk separately for vehicles with similar footprint. The analysis indicates that mass reduction does not consistently increase risk across all footprint deciles for any combination of vehicle type and crash type. Risk increases with decreasing mass in a majority of footprint deciles for 12 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, risk <u>decreases</u> with decreasing mass in a majority of footprint deciles for 5 of the 27 crash and vehicle combinations; in some cases these risk reductions are large and statistically significant. If reducing vehicle mass while maintaining footprint inherently leads to an increase in risk, the coefficients on mass reduction should be more consistently positive across the 27 vehicle/crash combinations.

3.2. Sensitivity of results to data used and model specification

We next ran alternative regression models to test the sensitivity of the results from NHTSA's "preferred" model to changes in how risk is defined, as well as the control variables and data used in the regression models.

3.2.1. Sensitivity to accounting for differences in vehicle models

One limitation to using logistic regression to estimate the effect of mass reduction on risk is that a standard statistic to measure the extent to which the variables in the model explain the range in risk, equivalent to the R^2 statistic in a linear regression model, does not exist. (SAS does generate a pseudo-R^2 value for logistic regression models; in almost all of the 27 regressions of NHTSA's preferred model this value is less than 0.10). For this reason we conducted an analysis of risk versus mass by vehicle model, using linear regression. Our analysis by vehicle model indicates that the variables included in the NHTSA preferred model only account for a small portion of the variability in risk by vehicle model (Wenzel 2012b). One suspects that other, more subtle differences among vehicle models, such as their general design or their drivers' behavior, may explain the large remaining variability in risk.

Models 8 and 9 in Table 2 attempt to account for differences in the general quality of vehicle design by vehicle model. Model 8 adds 19 dummy variables based on the vehicle nameplate: 14 manufacturers plus the luxury brands of the 5 largest manufacturers. Non-luxury GM brands (Buick, Chevrolet, GMC, Oldsmobile, Pontiac, and Saturn) are treated as the default value, since combined they represent the most vehicles by manufacturer, both in fatalities and VMT.[3] The five Chrysler brands (Jeep, Chrysler, Dodge, Plymouth, and Sprinter) were combined in a single Chrysler category, while the two non-luxury Ford brands (Ford, Mercury) were combined in a single Ford category. Ten low-volume manufacturers were grouped into a separate Other manufacturer category.[4] The five luxury brands (Cadillac, Lincoln, Acura, Infiniti, and Lexus) are identified separately as they are more likely to include specific safety technologies or generally superior design than non-luxury brands of the same manufacturer. Of the 20 dummy variables for car nameplate, 12 are associated with a statistically-significant increase in risk relative to the baseline car (GM non-luxury cars), one is associated with a significant decrease in risk, and the remaining seven are not statistically different from the baseline car. Seven light truck nameplates are associated with an increase in risk relative to the baseline GM light truck, while eleven CUV/minivan nameplates are associated with an increase in risk relative to the baseline GM CUV/minivan.

The effect of including the 20 nameplate variables in the regression models is that the estimated detrimental effect of mass reduction on risk is much higher in cars (2.04% vs. 1.55% for lighter-than-average cars, and a statistically significant 1.80% vs. 0.51% in heavier-than-average cars). It also substantially reduces the estimated detrimental effect of footprint reduction in cars (from 1.87% to 1.20%). Accounting for vehicle nameplate makes the estimated effect of mass reduction detrimental and statistically-significant (from -0.38% to 1.28%), while the estimated effect of footprint reduction becomes slightly beneficial (from 1.72% to -0.28%).

Initial vehicle purchase price, rather than manufacturer nameplate, is another proxy for the general quality of vehicle design. The initial purchase price was obtained from the Polk VIN decoder, using 2010 California registration data from the state Department of Motor Vehicles.

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[3] The 14 manufacturers are: Chrysler, Ford, BMW, Honda, Hyundai, Kia, Mazda, Mercedes-Benz, Mitsubishi, Nissan, Subaru, Toyota, Volkswagen, and Volvo.

[4] The manufacturers included in the Other category are: AM General, Audi, Daewoo, Isuzu, Jaguar, Land Rover, Mini, Porsche, Saab, and Suzuki.

Every $1,000 increase in initial purchase price is estimated to increase risk in cars by 0.21% (+/- 0.12%), but decrease risk in light trucks by 0.56% (+/- 0.11%) in light trucks and by 0.80% (+/- 0.27%) in CUVs/minivans. Model 9 in Table 2 shows how accounting for vehicle purchase price changes the estimated effect of mass or footprint reduction on risk, compared with NHTSA's preferred model. Including initial purchase price in the regression models substantially increases the estimated effect of mass reduction in heavier-than-average cars (from an estimated 0.51% to 0.84% increase in risk), and substantially increases the estimated beneficial effect of mass reduction in heavier-than-average light-duty trucks and CUVs/minivans. Accounting for initial vehicle purchase price increases the estimated beneficial effect of footprint reduction in light trucks, but results in little change in the estimated effect of footprint reduction on risk for cars and CUVs/minivans.

Accounting for vehicle purchase price tends to have a smaller effect on the estimated effect of mass reduction on risk than accounting for vehicle nameplate, except for heavier-than-average light trucks; accounting for price has a larger effect on the estimated effect of footprint reduction on risk than accounting for manufacturer.

3.2.2. Sensitivity to measures of driver behavior

It is possible the unexplained differences in risk among vehicle models is not due to the design of the vehicles themselves, but rather differences (other than age and gender) in who tends to own certain vehicle models and how they drive them. We tested the sensitivity of Kahane's estimates to two measures of driver behavior: alcohol/drug use and driving record (Model 12 in Table 2), and median household income (Model 13 in Table 2). FARS indicates that about 10% of car and light truck drivers, and 6% of CUV/minivan drivers, in fatal crashes were reported to have been drinking or engaged in drug use. In its 2003 report NHTSA created a "bad driver rating" variable based on whether the alcohol or drugs were involved in the current crash, as well as driving without a valid license or reckless driving in the current crash, and the driver's driving record in the last three years. These additional "bad" drivers account for another 11% of car and light truck drivers, and another 8% of CUV/minivan drivers, in the FARS cases. The effect of excluding case vehicles where the driver was reported to have been drinking or using drugs, or exhibited poor driving behavior, from the regression analysis was examined. Although fatal crashes involving case vehicles whose drivers were reported to have been drinking or using drugs or had poor driving records were excluded, no adjustments to the induced exposure cases from the 13 states were made.[5]

Model 12 in Table 2 indicates that excluding alcohol/drug users and bad drivers from the analysis further increases the estimated effect of mass reduction on risk. For example, the estimated increase in risk from mass reduction increases from 1.55% to 2.32% in lighter-than-average cars, from 0.51% to 1.19% in heavier-than-average cars, and from 0.52% to 1.01% in lighter-than-average light-duty trucks. On the other hand, excluding alcohol/drug users and bad drivers from the analysis further reduces the estimated detrimental effects of footprint reduction

[5] Most states report suspected driver alcohol or drug use, so in theory these induced exposure cases could be excluded, and the vehicle registration annual VMT weights recalculated used in estimating vehicle exposure. However, this adjustment would have to be done by NHTSA, as the vehicle registration data they used are not publicly available. Detailed information on a driver's record is generally not provided in the state crash data.

on risk. The fraction of drivers who are drunk, drugged, or bad drivers is two to three times higher in rollovers and fixed object crashes than in all other crash types. Because mass reduction is most beneficial, and footprint reduction most harmful, in these two types of crashes (as shown in Table 2), removing crashes involving these drivers from the analysis makes estimated overall mass reduction more harmful, and footprint reduction less harmful.

Household income can also act as a proxy for driver behavior; elsewhere (Wenzel 2012b) it is shown that there is a fairly strong correlation between household income and predicted fatality risk, with risk decreasing as income increases, and that crash frequency increases as household income increases, particularly for cars. Every $1,000 increase in household income is estimated to reduce US fatality risk per VMT 0.72% (+/- 0.26%) for cars, and 0.24% (+/- 0.16%) for light trucks, while increasing risk 0.04% (+/- 0.24%) for CUVs/minivans. Model 13 in Table 2 shows the estimated effect of mass or footprint reduction on risk after accounting for household income. Accounting for household income has a bigger influence on the estimated effect of mass or footprint reduction in cars than in light trucks or CUVs/minivans: accounting for household income substantially reduces the estimated effect of mass reduction in cars (for instance, from 1.55% to 1.20% in lighter-than-average cars), and substantially increases the estimated effect of footprint reduction in cars. This is in contrast to excluding the alcohol/drug use and bad driving behavior cases, which substantially increased the estimated effect of mass reduction in cars on risk (and reduced the estimated effect of footprint reduction).

4. Discussion

The four alternative model specifications that attempt to account for differences in the quality of vehicle design and driver behavior do not show consistent results. Including control variables for vehicle brands in the regression model, or excluding crashes involving alcohol, drugs, or bad drivers, tend to increase the detrimental effect of mass reduction on fatality risk. On the other hand, including a control variable for vehicle purchase price or median household income tends to reduce the detrimental effects of mass reduction. These results suggest that the estimated effect of reducing vehicle mass on fatality risk is sensitive to different methods to account for the general quality of vehicle design and driver behavior by vehicle model.

Table 4 compares the results from NHTSA's 2003, 2010, and 2012 analyses with the range in alternative model specifications examined in the 2012 studies. The first two columns of the table indicate that NHTSA's 2012 analysis of a simultaneous reduction in mass and footprint (i.e. excluding a control variable for footprint in the regression model) results in a smaller estimated increase in fatality risk than NHTSA's 2003 analysis, particularly for lighter cars (a 2.74% increase rather than a 4.39% increase) and light trucks (a 0.47% increase rather than a 2.90% increase). The third and fourth columns of Table 4 indicate a similar reduction in estimated additional fatalities for cars when footprint is held constant (i.e. when a control variable for footprint is included in the regression model). However, holding footprint constant increases the estimated effect of mass reduction slightly in light trucks (a 0.52% increase rather than a 0.17% increase in fatalities for lighter light trucks, and a 0.34% reduction rather than a 1.90% reduction in fatalities for the heavier light trucks). This small increase in light truck risk may be due to NHTSA analyzing crossover utility vehicles and minivans as a separate vehicle class, rather than as light trucks, in the 2012 analysis.

The last column in Table 4 shows that the results of the 19 alternative model specifications examined in 2012 are, in nearly all cases, lower than the results of the 2003 NHTSA report, and often lower than the results of the 2010 and 2012 analyses. The last column indicates that changes in the measure of risk, data, or control variables used in the regression analysis can result in small changes in the estimated effect of mass reduction on U.S. societal fatality risk per vehicle mile traveled.

Table 4. Previous NHTSA results of the estimated effect of a 45-kg reduction in mass or a 0.09-m^2 reduction in footprint on U.S. societal fatality risk per VMT, compared with 19 different sensitivities

Variable	Case vehicle type	NHTSA (2003) excluding footprint	NHTSA (2012) excluding footprint	NHTSA (2010) including footprint	NHTSA (2012) including footprint	Range of 19 alternative regression models analyzed
Mass reduction	Cars < 1433 kg	4.39%*	2.74%*	2.21%	1.55%*	-0.22% to 2.74%*
	Cars > 1433 kg	1.98%*	1.95%*	0.89%	0.51%	-1.45%* to 2.40%*
	LTs < 2247 kg	2.90%*	0.47%*	0.17%	0.52%*	-1.13%* to 1.20%*
	LTs > 2247 kg	0.48%	-0.39%*	-1.90%	-0.34%*	-0.97%* to 0.30%
	CUV/ minivan	—	0.60%*	—	-0.38%	-0.92% to 1.62%*
Footprint reduction	Cars	—	—	—	1.87%*	-0.09% to 3.43%*
	LTs	—	—	—	-0.07%	-1.30%* to 0.22%
	CUV/ minivan	—	—	—	1.72%	-0.77% to 2.26%*

* statistically significant at the 95% level.

5. Conclusions

In its report NHTSA concludes that "although [the 2010 NHTSA] report and this one both concentrate on the effects of mass and footprint, because that is their purpose, these effects are indeed small relative to design and engineering, which shape a vehicle's intrinsic safety and also bear indirectly on its fatality rates by influencing what types of drivers choose the vehicle." Our analysis agrees with the 2012 NHTSA study that the estimated effect of mass reduction on U.S. fatality risk is small; our sensitivity analyses indicate at most a 3 percent change in risk, for the lightest cars. The estimated effect of reducing mass in the lightest cars is consistently associated with a small increase in risk, for all but two of the 19 sensitivity scenarios analyzed. However, for the other vehicle types, mass reduction can lead to either a small decrease or a small increase in risk, depending on what control variables and data are used in the regression models. Therefore we conclude that the effect of mass reduction on U.S. societal fatality risk is statistically non-significant for all but the lightest cars. Based in part on these findings, the U.S. fuel economy and greenhouse gas emission standard levels adopted in 2012 assume that it is cost effective for manufacturers to reduce the mass of light trucks by up to 20% without increasing societal risk; the standard levels allow for a reduction in mass of up to 10% for large cars, and up to 3.5% for midsize cars (U.S. EPA and NHTSA 2012).

We have shown that although the estimated effects are sensitive to what variables and data are included in the regression analysis, in nearly all cases the effects are less, in some cases dramatically less, than reported in the 2003 NHTSA study. The estimated effects of other control variables, such as vehicle type, specific safety technologies, and crash conditions such as whether the crash occurred at night, in a rural county, or on a high-speed road, on risk are much larger, in some cases two orders of magnitude larger, than the estimated effect of mass or footprint reduction on risk. It appears that the safety penalty from lower mass can be mitigated with careful vehicle design, and that manufacturers can reduce mass as a strategy to increase their vehicles' fuel economy and reduce greenhouse gas emissions without necessarily compromising societal safety.

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